On the Performance of Cooperative Wireless Fixed Relays in Asymmetric Channels

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***Abstract*— In many scenarios the commonly assumed symmetry in multiple relay channels is unrealistic. Therefore, this paper, through analytical and simulation efforts, investigates asymmetric relay deployment where the links of cooperating nodes to destination experience unequal signal strength. An analysis of the cooperative error rate at the destination node in such networks is presented. Using the derived expressions for the cooperative error, in conjunction with the approaches used in earlier works, the end-to-end (E2E) performance of a two-hop network can be obtained. Moreover, the derived expression represents, in certain scenarios, a tight bound for the E2E error rate of the two-hop network such as when relay adopts threshold decode-and-forward strategy and/or multi-antenna processing to improve the reliability of its detection.**

I. Introduction

Spatial diversity, obtained through multiple antennas, is an effective way of combating fading in wireless channels. Multiple antenna techniques have been well-studied; the promises in these schemes are well-known. However, the application of these techniques to mobile systems often faces implementation challenges. For instance, it is inconceivable for small-size mobile terminals to bear a large number of antennas without the signals being highly correlated.

Techniques such as the cooperative use of resources belonging to mobile terminals or fixed relays are being considered to address the spatial limitations of terminals and to harness other benefits of relaying. This paper considers distributed fixed relays (deployed by the service provider) which are engaged in a cooperative manner to mimic a large array of antennas, thus, enabling the exploitation of spatial diversity in two-hop relay networks. Moreover, a network with intermediate relays benefits from reduced path loss in comparison to one without relays; these benefits are usually referenced but not quantified in previous works [1]. The analysis presented in this paper encompasses these benefits as well.

In conventional relaying, the destination relies only on the signal from the relay (Figure 1 (a)). This scheme ignores the broadcast nature of wireless transmissions. Cooperative relaying exploits this feature as shown in Figure 1 (b) where the relay collaboratively provides the destination with an independent copy of the source signal. By employing a suitable network protocol, the destination could benefit from the spatial diversity.

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A cost-effective and practical network cooperative protocol design is the one that satisfies the orthogonality constraints [2] [3]. In such design, the available radio resources (time or frequency) are divided between the receiving and transmitting phases of the relay which frees the relay from operating in full duplex mode (i.e., simultaneously transmitting and receiving on the same channel).

A simple description of the two-phase relaying protocol is the following. In the first phase, the source broadcasts its information while it is assumed that both the relay station and destination receive faded versions of this signal. The destination stores the signal it receives for future processing. In the second phase, the relay either does or does not forward a new (regenerated) signal to the destination. This conditional forwarding strategy is aimed at reducing the risk of error propagation. If the relay forwards, the destination combines its delayed (buffered) signal with the new version from the relay using maximal ratio combining (MRC). Otherwise, the relay is silent; the destination resorts to only the stored signal for decoding. The forwarding criterion could be that the received signal-to-noise ratio (SNR) is above a certain threshold or that the decoded block passes a cyclic redundancy check test. This strategy, therefore, can be classified as observe-then-decode-and-forward protocol.

This paper builds on the cooperative strategy described above with the following. First, it assumes a network with an arbitrary number of relays with arbitrary positions. We refer to such set-ups as asymmetric networks in contrast to the symmetric ones which are usually used in the literature [1]. In the symmetric networks the multiple relays are either treated as being at the same location as the source or that all the relays are at the same location and midway between the source and the destination. This is the assumption in most previous work, though convenient for analysis, it does not hold for many practical systems. Second, this paper considers a versatile Nakagami fading channel model while [4] uses Rayleigh which can be seen as a special case of this study. Furthermore, these relays could face different channel distributions to the destination. For example, some relay-destination links can

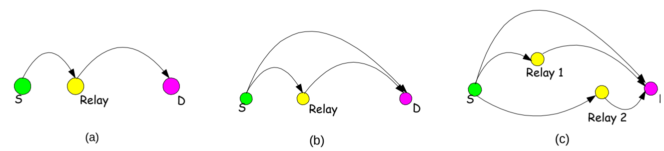

Fig. 1. Two-hop network configuration: (a) conventional relaying, (b) cooperative network, (c) cooperative network (parallel relays).

be modelled as a non-line of sight (Rayleigh fading) while others as a line of sight (Ricean fading). Therefore, it is easy to investigate different network topologies which is not the case with other works [4], [5]. Moreover, the end-to-end error performance formulation in [5] can be applied to this work with a few modifications. Such modifications are not undertaken in the present study.

II. Relay Networks with Unequal Link Average SNRs

In an asymmetric network scenario, all links can have different average SNRs. We represent these average SNRs as $\bar{\gamma}_i$, $i = 1, \cdots, N_R+1$, where N_R denotes the number of relays. Considering the two-hop network which is represented by the simple topology in Figure 1, and using the model in [6], the average SNR between a node r located at (x_r, y_r) and the destination located at $(x, 0)$ can be expressed as $\bar{\gamma}_r = \bar{\gamma}\left[\frac{x}{\sqrt{(x-x_r)^2+y_r^2}}\right]^n$, where n is the path loss exponent and $\bar{\gamma}$ is the average SNR for a single-hop source-destination link. For the purpose of simplicity, all the receiving nodes are assumed to have the same noise power. The total power of the transmitting nodes is the same as the transmit power of the reference single hop transmission.

In the following, we present the cooperative error performance component for the asymmetric network. This constitutes the second phase of the two-hop scheme. It will be demonstrated that in certain situations (such as, when S-R links are highly reliable) the derived expressions can be used as a quick means of evaluating the E2E network performance.

We first pursue the probability density function (PDF) of the output SNR, γ, of the destination receiver that uses MRC to process the signals received via the N_R parallel relays in cooperation with the source. Characteristic function (CF) approach [7] is employed. However, the moment generating function approach can also be used [9]. In this formulation and subsequent treatments the destination is assumed to receive signals from all relays. This implies that with the threshold decode-and-forward (TDF) protocol [4], [5], the received SNR at the relays is always above the decoding threshold or that the decoded block always passes the CRC test. These TDF and CRC techniques are used to combat the error propagation from the relays.

We recall that $\gamma = \sum_{i=1}^{N_R+1} \gamma_i$ and the Nakagami PDF of γ_i is given as

$$p_{\gamma_i}(\gamma_i, m_i) = \frac{m_i^{m_i} \gamma_i^{m_i-1}}{\bar{\gamma}_i^{m_i} \Gamma[m_i]} \exp\left(-\frac{m_i \gamma_i}{\bar{\gamma}_i}\right), \quad \gamma_i \geq 0, m_i \geq 1/2, \tag{1}$$

where m_i is the Nakagami parameter and $\Gamma[\cdot]$ is the gamma function.

The CF of a random variable γ_i is defined [7, p. 35, (2-1-71)] as $E(e^{j\upsilon\gamma_i}) \equiv \psi(j\upsilon) = \int_{-\infty}^{\infty} e^{j\upsilon\gamma_i} p(\gamma_i) d\gamma_i$, and with (1), the CF of a single branch SNR, γ_i, with Nakagami fading m_i can be expressed as $\psi_{\gamma_i}(j\upsilon) = \frac{1}{(1-j\upsilon\frac{\bar{\gamma}_i}{m_i})^{m_i}}$. Since γ is the sum of N_R+1 statistically independent components $\{\gamma_i\}$, the CF of γ is

$$\psi_\gamma(j\upsilon) = \prod_{i=1}^{N_R+1} \frac{1}{(1-j\upsilon\frac{\bar{\gamma}_i}{m_i})^{m_i}}; \tag{2}$$

and therefore, the PDF of γ can be obtained by taking the inverse Fourier transform of (2). This can be achieved by resolving (2) into its partial fractions. Afterwards, by employing [8, pp. 168, (4.43)-(4.44)] for multiple repeated roots (at $j\upsilon = \omega = \frac{m_i}{\bar{\gamma}_i}$) of order m_i, the PDF can be expressed as

$$p(\gamma) = \sum_{i=1}^{N_R+1} \sum_{k=1}^{m_i} \varrho_{i,k} \left(\frac{m_i}{\bar{\gamma}_i}\right)^k \frac{\gamma^{k-1}}{\Gamma[k]} \exp\left(-\frac{m_i\gamma}{\bar{\gamma}_i}\right), \tag{3}$$

where,

$$\varrho_{i,k} = \frac{1}{(m_i-k)!\left(-\frac{\bar{\gamma}_i}{m_i}\right)^{m_i-k}} \times \left\{\frac{\partial^{m_i-k}}{\partial\omega^{m_i-k}}(1-\frac{\bar{\gamma}_i}{m_i}\omega)^{m_i}\psi_\gamma(\omega)\right\}_{\omega=\frac{m_i}{\bar{\gamma}_i}}. \tag{4}$$

The error performance of a number modulation schemes can be evaluated using the PDF given above. For instance, when binary phase shift keying (BPSK) modulation format is adopted on all the links, the cooperative average bit error rate (BER) can be expressed in the following closed-form. The derivation is performed as follows:

$$\begin{aligned} P_e &= \frac{1}{2}\int_0^\infty \mathrm{erfc}(\sqrt{\gamma})\, p(\gamma)\, d\gamma, \\ &= \frac{1}{2}\sum_{i=1}^{N_R+1}\sum_{k=1}^{m_i} \varrho_{i,k}\left(\frac{m_i}{\bar{\gamma}_i}\right)^k \\ &\times \int_0^\infty \mathrm{erfc}(\sqrt{\gamma})\,\frac{\gamma^{k-1}}{\Gamma[k]}\exp\left(-\frac{m_i\gamma}{\bar{\gamma}_i}\right)d\gamma. \end{aligned} \tag{5}$$

After evaluating the integral part in the above expression, P_e becomes,

$$P_e = \frac{1}{2}\sum_{i=1}^{N_R+1}\sum_{k=1}^{m_i}\varrho_{i,k}\left(\frac{m_i}{\bar{\gamma}_i}\right)^k \frac{\Gamma[k+1/2]}{\sqrt{\pi}\,\Gamma[k+1]} \times\ {}_2F_1[k,k+1/2;k+1;-m_i/\bar{\gamma}_i], \quad (6)$$

where ${}_2F_1[\cdot,\cdot;\cdot;\cdot]$ is the hypergeometric function [10].

Further simplification can be performed in (6) by using [10, p. 1069 (9.131.1)] to express ${}_2F_1[k,k+1/2;k+1;\frac{-m_i}{\bar{\gamma}_i}]$ as $(\frac{\bar{\gamma}_i}{\bar{\gamma}_i+m_i})^k\ {}_2F_1[k,1/2;k+1;\frac{m_i}{\bar{\gamma}_i+m_i}]$. Finally using [10, p. 960 (8.391)], the following closed-form expression for P_e is obtained as

$$P_e = \sum_{i=1}^{N_R+1}\sum_{k=1}^{m_i}\varrho_{i,k}\frac{\Gamma[k+1/2]}{2\sqrt{\pi}\,\Gamma[k]}B_{x_i}[k,1/2], \quad (7)$$

where $x_i = \frac{m_i}{\bar{\gamma}_i+m_i}$ and $B_x[\cdot,\cdot]$ is the incomplete beta function.

The expression given in (7) can be employed in a number of scenarios to investigate the performance of two-hop communication networks. Sec. III discusses some scenarios where the derived expression could be used for evaluating the system performance.

III. Scenarios

The error performance expression (7) can be employed in a number of network scenarios:

- In delay-tolerant and low transmit power applications such as mobile infostation network [11]. An example of such application is the following. A source node wants to deliver certain packets to a destination node. This source could identify two intermediate nodes (e.g., 1 and 2) that pass by and it relays its packets to them. These relay nodes however are not the destination of these packets. When each of the relay nodes (1 and 2) approaches the destination, it will, on behalf of the source node, forward the packet to the destination to complete the second hop of the relaying. Note that due to mobility the relay-destination channels are not expected to be the same. In this scenario the expression (7) represents a good estimate of the system performance since the first hop is conducted while the source is favorably close to the relay nodes.
- The expression represents a good estimate of the performance of a two-hop cooperative relay network when powerful codes or other error management schemes are employed to ensure reliable source-relay channel and thereby mitigating relay error propagation. In this case, (7) represents a tight bound for the system performance. In the numerical examples section we will demonstrate that the expression is a tight bound for the system performance of threshold decode and forward (TDF) relaying strategy. For instance, the E2E error performance of threshold decode and forward relaying protocol $P_{\text{E2E, TDF}}$ can be lower bounded as $P_{\text{E2E, TDF}} \geq P_e$. The aforementioned examples are scenarios where (7) can be a stand-alone expression. However, complementing the work in [4], [5] appropriate modifications of their analytical results for symmetric networks can be performed and in conjunction with (7), the exact E2E error performance of the asymmetric networks can be obtained. Such modifications are straightforward. We will therefore not embark on them in this paper.

IV. Numerical Illustrations

Four cases have been considered to illustrate the performance of the asymmetric relay channels. Simulations results as well as demonstration of the use of (7) are discussed in this section.

Cases I and II have one and two cooperating relays, respectively, and all the links are assumed to experience Rayleigh fading ($m = 1$). Cases III and IV have also one and two cooperating relays, respectively, but the links are of mixed modes described as follows: Case III consists of a cooperative relay positioned to have line-of-sight (LOS) link to destination. To this end, we use Ricean fading model with a K factor of 3.83 dB which is equivalent to the Nakagami parameter $m = 2$. Finally, Case IV considers two cooperative relays both with LOS links to destination with Ricean $K = 3.83$ dB.

Let the source-destination (S-D) link be denoted as channel 1, with parameters m_1 and $\bar{\gamma}_1$. The m parameter and average SNR for the relay-destination (R-D) links (which constitute the second hop) are m_i and $\bar{\gamma}_i$, respectively, $i = 2,3$. The factors $\varrho_{i,k}$ required for evaluating (7) can be computed as follows:

In the following illustrations note that $\gamma_i\, m_k \neq \gamma_k\, m_i$.

- **Case I.** One cooperating relay, with $m_1 = 1$ and $m_2 = 1$. The following factors have to be computed

$$\varrho_{1,1} = \frac{\bar{\gamma}_1}{\bar{\gamma}_1-\bar{\gamma}_2} \text{ and } \varrho_{2,1} = \frac{\bar{\gamma}_2}{\bar{\gamma}_2-\bar{\gamma}_1}. \quad (8)$$

- **Case II.** Two cooperating relays, with $m_1 = 1$, $m_2 = 1$, and $m_3 = 1$. Then,

$$\varrho_{1,1} = \frac{1}{(1-\frac{\bar{\gamma}_2}{\bar{\gamma}_1})(1-\frac{\bar{\gamma}_3}{\bar{\gamma}_1})},$$
$$\varrho_{2,1} = \frac{1}{(1-\frac{\bar{\gamma}_1}{\bar{\gamma}_2})(1-\frac{\bar{\gamma}_3}{\bar{\gamma}_2})},$$
$$\varrho_{3,1} = \frac{1}{(1-\frac{\bar{\gamma}_2}{\bar{\gamma}_3})(1-\frac{\bar{\gamma}_1}{\bar{\gamma}_3})}. \quad (9)$$

- **Case III.** One cooperative relay, with $m_1 = 1$ and $m_2 = 2$. We need to evaluate $\varrho_{1,1},\ \varrho_{2,1}$, and $\varrho_{2,2}$.

$$\varrho_{1,1} = \frac{1}{(1-\frac{\bar{\gamma}_2}{2\bar{\gamma}_1})^2}, \varrho_{2,1} = \frac{-2\frac{\bar{\gamma}_1}{\bar{\gamma}_2}}{(1-\frac{2\bar{\gamma}_1}{\bar{\gamma}_2})^2}, \text{ and}$$
$$\varrho_{2,2} = \frac{1}{(1-\frac{2\bar{\gamma}_1}{\bar{\gamma}_2})}. \quad (10)$$

- **Case IV.** Two cooperative relays, with $m_1 = 1$, $m_2 = 2$, $m_3 = 2$. In this case we need to compute $\varrho_{1,1},\ \varrho_{2,1},\ \varrho_{2,2},\ \varrho_{3,1}$, and $\varrho_{3,2}$. These factors can be expressed as

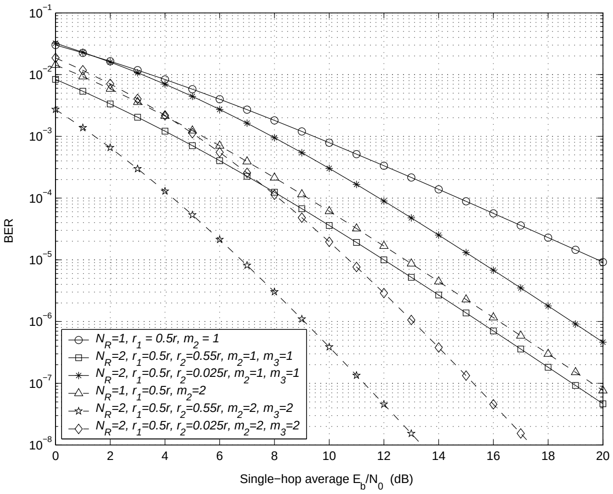

Fig. 2. Cooperative error performance at the destination of a two-hop relay network.

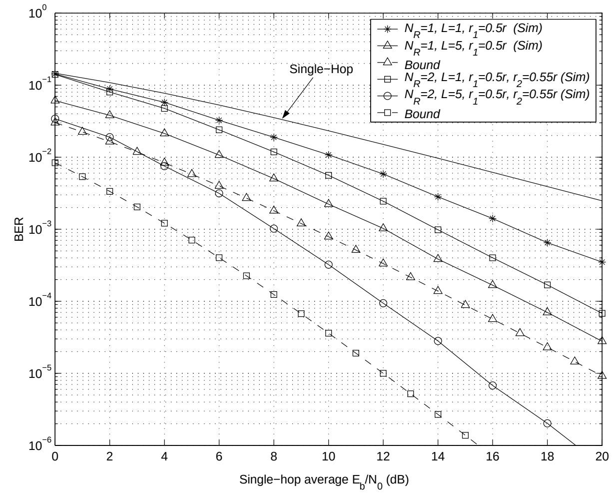

Fig. 3. Comparison of the bound and simulated end-to-end error performance of relay networks in Rayleigh fading.

$$
\begin{aligned}
\varrho_{1,1} &= \frac{1}{(1-\frac{\bar{\gamma}_2}{2\bar{\gamma}_1})^2(1-\frac{\bar{\gamma}_3}{2\bar{\gamma}_1})^2}, \\
\varrho_{2,1} &= \frac{-2}{\bar{\gamma}_2}\Big(\frac{\bar{\gamma}_3}{(1-2\bar{\gamma}_1/\bar{\gamma}_2)(1-\bar{\gamma}_3/\bar{\gamma}_2)^3} \\
&+ \frac{\bar{\gamma}_1}{(1-2\bar{\gamma}_1/\bar{\gamma}_2)^2(1-\bar{\gamma}_3/\bar{\gamma}_2)^2}\Big), \\
\varrho_{2,2} &= \frac{1}{(1-2\bar{\gamma}_1/\bar{\gamma}_2)(1-\bar{\gamma}_3/\bar{\gamma}_2)^2}, \\
\varrho_{3,1} &= \frac{-2}{\bar{\gamma}_3}\Big(\frac{\bar{\gamma}_2}{(1-2\bar{\gamma}_1/\bar{\gamma}_3)(1-\bar{\gamma}_2/\bar{\gamma}_3)^3} \\
&+ \frac{\bar{\gamma}_1}{(1-2\bar{\gamma}_1/\bar{\gamma}_3)^2(1-\bar{\gamma}_2/\bar{\gamma}_3)^2}\Big), \\
\text{and} \quad \varrho_{3,2} &= \frac{1}{(1-2\bar{\gamma}_1/\bar{\gamma}_3)(1-\bar{\gamma}_2/\bar{\gamma}_3)^2}.
\end{aligned} \tag{11}
$$

Figure 2 shows the cooperative error performance at the destination using expression (7). Different network configurations are considered and BPSK modulation format has been employed. A path loss exponent of $n = 3$ has been used. Since we are interested in the diversity benefit due to cooperative multiple relays we have not searched for the optimum placements for the relays. Provided that the relays are positioned well-enough to ensure reliable decoding the effect of the positions of the relay will only move the curves that are shown without changing the slope, i.e., the diversity order. Having said that, for single cooperating relay, the relay is located midway between the source and destination in this study. The solid curves represent the case with Rayleigh fading in all links and the dotted ones represent those in which the relays experience LOS links. The fact that all cases have the same total transmit power implies that as the number of relays increases the power of each transmitting entity decreases. Reducing the transmit power requirement of transmitting nodes could be an efficient system deployment strategy with the following advantages: extending battery life-span for terminals, reducing interference, ensuring lower cost of power amplifier, ultimately leading to inexpensive terminals.

In Figure 2 it is observed that the performance of Case II is better than that of Case I. In addition, the performance of Case IV is superior to that of Case III. This performance superiority is in the diversity order measured through the slopes of the performance curves; the curves for Case II and Case IV are steeper than that of Case I and Case III, respectively. The aforementioned gain can be obtained if the detection of the relays is highly reliable and the relay forwards at all times. In view of this, these performance curves represent the lower bounds of the system performance. For this reason, we embark on end-to-end system performance simulations to investigate the usefulness of this expression for approximating the system performance. The protocol and decoding threshold used in [4] have been employed.

Figure 3 shows the bounds for all-Rayleigh links for relay positions $r_1 = 0.5r$ for $N_R = 1$, and $r_1 = 0.5r \,\&\, r_2 = 0.55r$ for $N_R = 2$. Multiple antennas (M) can be used at the relays to improve the source-relay (S-R) link. The significant impact of S-R link is observed when $M = 5$ (improved S-R link reliability) is compared with $M = 1$. The bound is tight for a reliable S-R link. The bound is within 2 dB from the simulated results for $N_R = 1$ with $M = 5$. The difference between the bound and simulated results becomes larger for higher numbers of relays. This is partly due to the fact that the bound assumes very reliable S-R links, whereas simulations do not make such an assumption. We can, however, infer from the results that as N_R increases, the reliability of S-R links becomes more crucial because of bandwagon effects of decoding errors at the relays. Comparison of the bound with other channel scenarios indicate the same performance patterns.

Another scenario where the bound could be an accurate representation of the system end-to-end performance is when

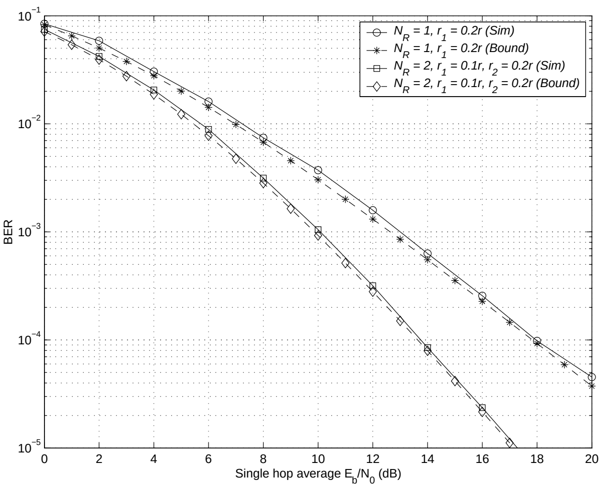

Fig. 4. Comparison of the bound and simulated end-to-end error performance of relay networks in Rayleigh fading.

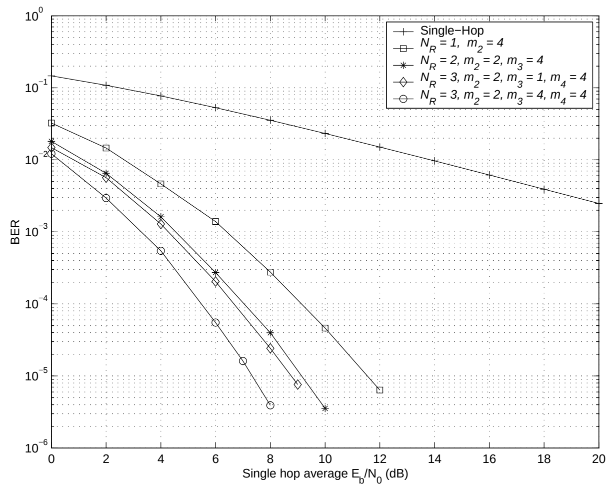

Fig. 5. End-to-end BER performance of relay networks with different relay locations and different m-parameter.

the relays are very close to the source. The results for this scenario are shown in Figure 4. The relays are placed at locations $r_1 = 0.2r$ for $N_R = 1$, and $r_1 = 0.1r$ & $r_2 = 0.12r$ for $N_R = 2$. The parameter $m = 1$ has been used in this example. It is observed that the bound is very tight in this scenario where the relays decode reliably because of their proximity to the source.

Figure 5 shows the impact of large relay networks and strategic relay locations in the cooperative scheme. The relay networks that have been considered are $\{N_R = 1, r_1 = 0.5r\}$, $\{N_R = 2, r_1 = 0.5r, r_2 = 0.55r\}$, and $\{N_R = 3, r_1 = 0.5r, r_2 = 0.55r, r_3 = 0.45r\}$. The Nakagami parameter adopted in the link between relay i and the destination is designated as $m_{i+1}\,(i = 1, 2, 3)$ and the S-D link is designated as m_1. The Nakagami parameters for the S-R and S-D links have been set to one. In general, $m_{i+1} > 1\,(i = 1, 2, 3)$ implies that the relays are placed at locations such that they establish a LOS link to destination whereas in the case of S-R links such LOS cannot be guaranteed, this is the justification for the $m = 1$ (Rayleigh) in these links. Note that $m = 4$ corresponds to a Ricean factor $K = 8.11$ dB.

The scheme with one cooperating relay ($N_R = 1$) with a LOS $K = 8.11$ dB link to destination ($m = 4$) greatly outperforms the single-hop Rayleigh channel. The curves denoted with asterisk and diamond indicate that for additional nodes to be effective they should have reasonably good links to destination. It can be observed that the network configuration with $N_R = 3$, $m_2 = 2$, $m_3 = 1$, and $m_4 = 4$ does not yield any significant performance improvement over that with $N_R = 2$, $m_2 = 2$, and $m_3 = 4$.

V. Conclusion

In this paper, we investigate the cooperative diversity achieved when multiple relays and source enter into cooperation in two-hop wireless asymmetric networks. In such networks, the signals in all the links have independent and non-identical channels. In contrast, most previous work have considered symmetric channels.

Normalization of transmit power has been performed in the multi-relay to ensure fair comparison among the different relay architectures; as the number of relays increases the power allocated to each transmitting entity decreases. This reduction in the transmit power requirement of nodes and user terminals could be an efficient system deployment strategy with the following benefits: extending battery life-span for terminals, reducing interference, ensuring lower cost of power amplifier, ultimately leading to inexpensive terminals.

Analytical and simulation results are provided for the two-hop networks for different network configurations of relays and in a wide range of channel distributions using the versatile Nakagami fading channel model.

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